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Implications of Perception Thresholds for Soiling

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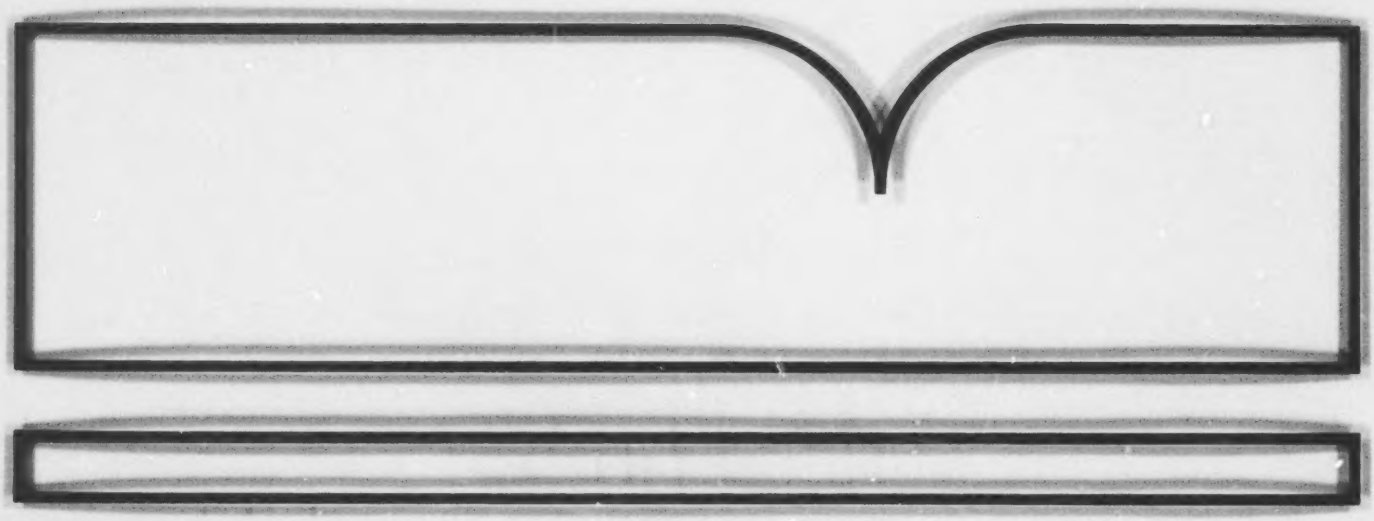

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16. ABSTRACT

Soiling of materials and visibility reduction are the two most important welfare effects of particulate matter. Though the relationship between fine particles and visibility reduction is well documented, the evidence for the relationship of ambient particles to soiling is scant and poorly understood. Considerable uncertainty exists concerning the amount of surface accumulated particulate matter that leads to a decision to clean, since not only are socioeconomic factors involved in such a decision, but accumulation of the particles must first be perceived as soiling. Information regarding relevant physical and chemical properties of airborne particles are reviewed (e.g. factors affecting deposition velocity and color). Considerations to assure congruency between physical measurement techniques and human observations are discussed. Factors are recommended for inclusion in development of psychophysical models to relate psychological and physical scales of soiling.

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Implications of Perception Thresholds for Soiling

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Abstract

There is general agreement that the most important welfare effects attributable to airborne particulate matter are visibility reduction and soiling of materials. The relationship between fine particulate matter and visibility is one of the best-documented in air pollution research. Visibility can be characterized, quantified, and defined with reasonable precision. Soiling has been defined operationally, e.g., as that condition which can be reversed by cleaning, since no generally accepted units of measurement have been developed for the effect. Considerable uncertainty exists concerning the amount of accumulated particulate matter that leads to cleaning, since not only are socioeconomic factors involved in a decision to clean, but accumulation of particles must first be perceived as soiling. Studies addressing this issue suggest no particular size range or level of particulate matter as uniquely influential in producing adverse effects. Total suspended particulate matter continues to be used as the indicator for soiling, though no effort has been made to calibrate measurement methods to human observation or perception. By contrast, with regard to visibility, considerable effort has been expended to assure congruency between physical measurement techniques and human observation. A similar interdisciplinary approach to soiling has been lacking. Psychophysical measures to identify absolute and differential thresholds of perceived soiling are necessary to evaluate the welfare effects of soiling attributable to particulate pollution.

Introduction

The welfare effects generally accepted as associated with particulate matter are visibility reduction and soiling of materials, both of which are related to human visual perception. The relationship between airborne particles and visibility is one of the best-documented in air pollution research. The atmospheric sciences have produced detailed information on the relative contribution to visibility reduction of the various subcomponents of airborne particulate matter by size and chemical composition and, therefore, to some degree by emission source. Since the judgment of the human observer is the ultimate reference for any evaluation of visual air quality, efforts have been expended to correlate the several instrumental methods developed for measuring visibility with human observation. A similar approach has been lacking in the evaluation of soiling attributable to airborne particles.

Whether a physical event has any existence absent from human perception has long been the subject of philosophical debate (e.g., Berkeley's tree in the forest). In the area of welfare effects, the matter becomes unequivocal: If welfare is not affected, there is no effect. The question, then, is how do airborne particles affect societal welfare in the area of soiling? A flow chart for analysis of factors contributing to soiling welfare effects is depicted in Figure 1.

Airborne particulate matter deposits at some rate on a surface. The resulting particle accumulation produces a physical effect that can be measured by instrumental means. This physical effect at some level provokes a visual response. At some level, the visual response is characterized as offensive. This aesthetic effect at some level provokes a behavioral response either to remove the offending particles from the affected surface, or to accept the visual insult. The result of both behavioral responses--either utility lost or resources expended--may be assigned a dollar value. The magnitude of the economic effect depends upon the activity necessary to remove the actual offense.

The distinction between soiling effects and two other welfare effects--material damage and visibility--can be drawn clearly. Material damage occurs when particle accumulation alters a surface in a way that is not reversible by a cleaning operation. Visibility is not related to any surface, but to one medium, ambient air. For that reason, all decisions regarding acceptable visual air quality must be made by society as a whole, since remedial action by any individual would be ineffective. One cannot, after all, clean the air as one might clean a surface. Otherwise, visibility and soiling effects of airborne particles share a number of aspects. Though an individual can gain some relief from the welfare effects of materials damage or soiling, amelioration of the total effects on society, especially with regard to publicly owned property, must be a societal decision.

Air pollution literature addressing visibility as a welfare effect of airborne particles has been fairly thorough in addressing the relationship of airborne particles to physical effect (extinction) and the physical effect's relationship to the sensory effect (visual range). The importance of the aesthetic and economic effects is recognized, and some success has been achieved in relating these effects to other effects and to the amount and kind of airborne particles.

PROBABLE INFLUENTIAL FACTORS	SEQUENCE OF EVENTS RELATING TO SOILING
PARTICLE SIZE WINDSPEED SURFACE ROUGHNESS SURFACE TEMPERATURE SURFACE ORIENTATION	AIRBORNE PARTICLES → DEPOSIT ? (NO → NO ADVERSE SOILING EFFECT) (YES) → SURFACE PARTICLE ACCUMULATION
PARTICLE OPTICAL PROPERTIES SURFACE OPTICAL PROPERTIES	SURFACE OPTICAL PROPERTIES ALTERED ? (NO → NO ADVERSE SOILING EFFECT) (YES) → OPTICAL EFFECT
CONTRAST OBSERVER VISUAL ACUITY OBSERVER COLOR PERCEPTION OBSERVER DISTANCE FROM SOURCE	SENSED? (NO → NO ADVERSE SOILING EFFECT) (YES) → PERCEIVED ACCUMULATION
OBSERVER SOCIOECONOMIC STATUS OBSERVER ATTITUDES (CULTURAL) PURPOSE IN USE OF SURFACE	OFFENSIVE? (NO → NO ADVERSE SOILING EFFECT) (YES) → AESTHETIC OFFENSE
OBSERVER SOCIOECONOMIC STATUS OBSERVER ATTITUDES PURPOSE IN USE OF SURFACE	TAKE ACTION? (YES → ECONOMIC EFFECT (RESOURCES EXPENDED)) (NO → ECONOMIC EFFECT (UTILITY LOSS))

Figure 1. Factors contributing to soiling effects of deposited particles.

Evidence for the relationship of ambient particles to welfare effects associated with soiling of materials is, by comparison with visibility, scant and poorly understood. Often the welfare effect has been defined in terms of one of the several effects depicted in Figure 1. The variety of terms and definitions used to describe the welfare effect in question illustrates the inconsistency of the literature. Hancock et al.[1] described the effect in sensory and aesthetic terms: "Dustiness is a visually perceived phenomenon . . . dustfall is a visual offense." Beloin and Haynie[2] took a theoretical approach: "Soiling is the accumulation of particulates on the surface of a material: Soiling is a continuous function of time and particulate concentration. Thus, if there is any particulate pollution there will be some soiling after any passage of time."

Table I illustrates very limited information about the tenuous connections between airborne particles and the various stages of particle surface effects associated with soiling, as developed in literature cited in the criteria document for sulfur oxides and particulate matter.[3] Thus, the vertical columns labeled physical, sensory, aesthetic, and economic effects show the kind of consideration given by the cited study to that particle surface effect. It is clear that no single study has considered all of these effects and their interrelationships.

If the relationships of all effects to each other and to the amount and kind of particles in the air were described in a generally applicable mathematical expression, there would be no problem with addressing only one aspect of particle soiling effects to evaluate the implications for societal welfare. This is, however, not the case. The very few damage functions developed from research to link surface exposure to soiling effects of suspended particulate matter (Beloin and Haynie[2]; Watson and Jaksch[13]) are inconsistent in form and address a limited number of possible surfaces and contributing factors.

During the decade since most research on soiling effects of airborne particles was performed, a considerable body of information has been developed regarding the physical and chemical properties of aerosol particles. Similarly, understanding of human perception has advanced during the same period. In the following discussion, we shall summarize the results of these research areas relevant to factors contributing to soiling effects and discuss the implications for assessment of these welfare effects associated with airborne particles. For example, nowhere in the Table I studies is there any pollutant data that would now be considered as valid measurement of ambient particle concentration by current quality assurance standards. It is recognized that considerable uncertainty exists in current assessments; a clearer delineation of the nature and degree of this uncertainty may provide a more objective basis for decision making. Carey[8] argued that "there appears to be a prima facie case for avoiding dinginess by controlling the rate of atmospheric coverage on the principle that the public will not be inconvenienced by a nuisance which they are unable to perceive." Even in the event that Carey's view should prevail, some agreement on the relationship of perceptible particle accumulation on various surfaces to ambient particle levels would be necessary. In the discussion that follows, factors to consider in reaching such agreement through investigative research are identified and discussed.

Table I. Summary of literature addressing factors contributing to soiling effects.

Study	Pollutants Units (Term)	Pollutant Data Source	Index Term, Particle Surface Effect Addressed				Comments
			Physical	Sensory	Aesthetic	Economic	
O'Connor[4]	Smoke, number of days/year visible smoke observed	U.S. Weather Bureau	?[a]	?	"It is safe to say that if it were possible to secure figures on "the disagreeableness of it all" it would equal one-fourth of of the total of all the items of cost."	$/yr incremental cleaning costs associated with smoke	Related increased cleaning and associated costs to number of smoke days/year. Incremental cost of cleaning for Pittsburgh area estimated at $9.9 million/year.
Michelson and Tourin[5]	Air pollution, $\mu g/m^3$	Consumer Reports	?	?	?	$/yr incremental cleaning costs associated with particulates	Cleaning activity frequency and cost data gathered via survey. Task frequency related to particle concentration, and multiplied by task cost to estimate increment.
Michelson and Tourin[6]	Suspended particulates, $\mu g/m^3$	Not described; "some ...data obtained from Maryland Department of Health"	?	?	?	$/yr incremental cleaning costs associated with particulates	
Michelson and Tourin[7]	Suspended particulates, $\mu g/m^3$	Connecticut State Department of Health	?	?	?	$/yr incremental cleaning cost associated with particulates	

Table I. Summary of literature addressing factors contributing to soiling effects (continued).

Study	Pollutants Units (Term)	Pollutant Data Source	Index Term, Particle Surface Effect Addressed: Physical	Sensory	Aesthetic	Economic	Comments
Carey[8]	Atmospheric dust, tons/mi^2/mo	Calculated and from the Department of Scientific and Industrial Research (U.K.)	% area coverage	% area coverage noticeable by panel	% area coverage found offensive by panel	?	% area of white horizontal surface covered by dust related to ambient particles by calculating deposition velocity. All particles contributing to effect assumed "fine" (<30 μm) and produced from fuel combustion Panel used to ascertain % of area coverage at which panel a) observed deposit and b) found deposit offensive. Assumed rainfall every 10 days to accomplish outdoor cleansing; dusting every four days indoors.
Narayan and Lancaster[10]	Dustfall, tons/mi^2/mo	Newcastle City (Australia) Department of Health	?	?	?	$/yr incremental costs of household upkeep	Compared cleaning and maintenance costs for 2 areas differing in dustfall level.
Esmen[11]	Dustfall			?	?	?	Proposed settled dust photometer for measuring soiling potential in terms of percent area per unit time.
Hancock et al.[1]	Dustfall, tons/mi^2/mo	Calculated from % effective area coverage rate	% effective area coverage	% effective area coverage detected by panel	% effective area coverage found offensive by panel	?	Used panels to identify levels of dust coverage that determine thresholds of detection, discrimination, and identification.

Table I. Summary of literature addressing factors contributing to soiling effects (continued).

Study	Pollutants Units (Term)	Pollutant Data Source	Index Term, Particle Surface Effect Addressed				Comments
			Physical	Sensory	Aesthetic	Economic	
Booz, Allen and Hamilton[12]	Particulate matter, $\mu g/m^3$	National Air Pollution Control Administration	?	?	Analysis included "attitudes toward cleanliness" as variables.	Cleaning/maintenance task performance frequency	Found though frequency of cleaning in some cases related to suspended particulate level expenditures for cleaning not related. Did not consider value of homeowner labor.
Beloin and Haynie[2]	Total suspended particulate matter, $\mu g/m^3$	Jefferson Co. (AL) Health Department	% change in reflectance (change in haze for glass)	?	?	?	Building materials exposed for two years at Birmingham site. Regression analysis showed time and particle concentration significant variables for reflectance change for white surfaces; color was addtional significant factor for brick. Poor correlations found for concrete, limestone, and window glass.
∞ Watson and Jaksch[13]	Particulate matter, $\mu g/m^3$	Booz, Allen and Hamilton[12]	Used Beloin and Haynie[2] and Esmen[11] data.	?	Used Booz, Allen, and Hamilton[12]	$/year benefit (welfare gain), reduction of particulate level.	Used portions of Booz, Allen and Hamilton[12] data to construct demand curve for household cleanliness. Values derived from Esmen[11] and Beloin and Haynie[2] used for various supply curves. Case worked for Philadelphia SMSA extrapolated to estimate national welfare benefit.

[a] ? = not addressed in developing relationship between surface particle effect and/or ambient particle concentration.

Particle Properties

A necessary condition for soiling of surfaces is accumulation of a perceptible mass of contrasting particulate matter on a surface. This condition involves three physical properties of the deposited particles. Atmospheric particles have characteristic deposition velocities, concentrations and color; this section explores the interplay of these factors likely to occur in real situations.

The rate that particles accumulate on surfaces is related to deposition velocity and mass concentrations by the following expression:

$$\text{Accumulation Rate } (\mu g/m^2/sec) = \text{Deposition Velocity (m/sec)} \times \text{Concentration } (\mu g/m^3)$$

Considerable insight into the role of particle physical properties in soiling can be gained by examining the typical ranges of values for deposition velocity and mass concentration.

Particle deposition velocities are a strong function of the particle size and of the roughness scale of the surfaces on which deposition occurs. These factors have been discussed rather thoroughly by Hicks.[14] To demonstrate the importance of these two factors, Table II presents evidence for wind tunnel and field studies of particle deposition. In the first case, water is used as a smooth surface and grass is taken as an example of a rough one. It is clear that fine particles, those smaller than about 1 micrometer, are deposited much less rapidly to both rough and smooth surfaces than are particles of, say, 10 micrometers in diameter. Generally, deposition velocities for 0.1 to 1.0 μm particles are in the order of 0.01 cm/sec for smoother surfaces and 0.05 to 0.1 cm/sec for rougher ones. For coarse particles, the characteristic deposition velocities are a steep function of particle size. However, for those sizes which account for a substantial fraction of coarse particle mass, say 8 to 20 μm, a range of deposition velocity from approximately 0.5 to 10 cm/sec is reasonable. Therefore, of the two modes of particle size which account for the mass of particles suspended in air, the coarse mode deposits from 50 to 1000 times more rapidly than the fine mode.

Table II. Particle dry deposition velocities, cm/sec.
(Adapted from Hicks[14])

Particle size, μm	Surface			
	Water (smooth)	Dry gravel ($16\ m\ s^{-1}$)	Dry gravel ($2.4\ m\ s^{-1}$)	Grass
0.1	0.01	0.06	0.01	0.04
0.5	0.01	0.05	0.01	0.04
1.0	0.02	0.05	0.02	0.05
5.0	0.1	6	0.1	0.7
10.0	0.4	10	0.4	1.5
20.0	1	5	1.5	3

The mass concentration of atmospheric particles is almost always observed to occur in two distinctly different size modes.[15] The finer particles, or accumulation mode, occur with a maximum in concentration between 0.4 and 0.7 μm. There is generally a broad minimum in the mass-size curve around 2 to 3 μm and a second coarse maximum somewhere around 20 μm. Finer particles have their origin in gas-condensation processes whereas the coarse ones are generally produced by frictional or grinding processes.

In 1959, Carey[8] noted a distinction between coarse and fine particle deposition rates in relation to particle sources. "When dust is discharged from chimneys it mixes with the wind, the coarse fractions settle within a mile and the fines spread across the country leaving a trace on the ground." However, he attributed deposition almost exclusively to the particle fraction we call "coarse" today. In fact, a common method for estimating particle concentrations was by the DSIR "Dustfall gauge." There is now a substantial amount of information on mass concentration of particles as a function of size mode and these data have been summarized in Chapter 5 of the criteria document for sulfur oxides and particulate matter.[9] Most of the recent data have been obtained with dichotomous samplers equipped with 10-μm or 15-μm inlets. In some cases these data have been obtained in parallel with TSP measurements by Hi-Vol sampling.

Table III presents a short summary of some mass fraction data obtained in several U.S. cities together with some measurements made at remote sites in the east[16] and others from an extensive study of remote sites in the western states.[17] East Coast values for fine particle mass are generally in the area of 15-20 $\mu g/m^3$. Coarse particle mass in the east is far more variable, however. In remote areas reported values are in the range 2 to 10 $\mu g/m^3$, while in cities the values are higher, usually around 15 to 45 $\mu g/m^3$ for dichotomous sampler coarse cuts. Fine particle concentrations for remote areas in the west have been reported at around 5 $\mu g/m^3$, while average coarse particle concentrations were about 2 $\mu g/m^3$ for 12,000 pairs of determinations.[16] When particles larger than 10 to 15 μm are included in this analysis, the variability in relationship of coarse to fine particle mass becomes even greater. It is clear that in some southwest cities, the coarse particle mode can be dominant, although there are some dramatic differences in particle size for the coarse mode. In the criteria document[9] two cases were cited where the coarse mode seemed to disappear almost entirely. In the Pacific Northwest in winter samples, the coarse mode was nearly absent because of extensive wet scavenging. Similarly in Litchfield, Connecticut in January and February the coarse mode disappeared because of snow cover. The criteria document identified roadway-produced fugitive dust as a major contributing factor to the coarse particle mass; apparently, there are situations in which snow cover can essentially suppress this source.

In the majority of cases examined, the coarse plus supercoarse particle concentration exceeds that of the fine. Considering the deposition velocity ratio, most probably the surface accumulation rate of coarse particles is greater than fine particles by a factor of 100 to 2000 for many cities. The exceptions noted were for cities in the southwest where dust levels are considerably higher than in the east and for climatic situations where precipi-

Table III. Dichotomous sampler and TSP data from selected sites--arithmetic averages.[9]

Location	Fine,[a] µg/m³	Coarse,[a] µg/m³	Super-coarse,[2] µg/m³
Northeast			
Buffalo, NY	25.9	25.2	21.9
Erie County, NY (remote)	16.2	5.1	10.0
Litchfield, CT (remote)	13.3	6.6	3.2
Philadelphia, PA	22.5	13.3	7.3
Southeast			
Birmingham, AL	24.4	15.0	18.5
Midwest			
Minneapolis, MN	16.4	15.6	20.5
Cincinnati, OH	25.2	14.4	11.8
Southwest			
Dallas, TX	24.1	9.8	38.2
El Paso, TX	11.7	46.3	55.9
Far West			
Los Angeles, CA	24.6	21.3	40.7
Portland, OR	22.0	42.3	7.1
Pearl City, HI	8.4	7.9	21.3
Remote Sites			
40 Western Remote Sites[17]	2.6	5.0	---
Shenandoah Park, VA	26.3	7.4	---
Smoky Mountains	24.0	5.6	---

[a]Fine and coarse particle fractions are those collected by dichotomous sampler with an upper cutoff of 15 µm and a midrange split at 2.5 mm (corresponds to PM 15).

[b]Super-Coarse (SC) refers to the difference between the total mass collected by dichotomous sampler and that collected on a high-volume filter. Thus, SC = TSP - [fine + coarse].

where precipitation scavenging removes coarse matter or where snow cover prevents its reentrainment.

There is also some evidence to characterize the concentrations of coarse and fine particles indoors. It is difficult to establish deposition rates inside a building or residence because there are no wind fields to compare with those outdoors; therefore, turbulent diffusion cannot be as important as would be the case outdoors. Furthermore, there appears to be little or no relationship between coarse particle levels indoors and those outdoors, while fine particle concentrations are almost equal in the two situations.[9] For these reasons, soiling assessments which extrapolate to indoor conditions are not likely to be correct.

The last particle property of significance in soiling is particle color. Generally the substances present in atmospheric aerosols have not been characterized by color, but there are some indications from chemical analysis of particle-size segregated samples which can provide some important perspectives. Chemical analysis has identified two possible colored components of particle mass, and microscopical examination has suggested one or two more.

Probably the most intensely colored component of atmospheric particulate material is black elemental carbon or soot. Stevens et al.[16] have found this material almost exclusively in the fine particle mass. Novakov[18] reported fine particle carbon concentrations in the range 1 to 5 $\mu g/m^3$ (annual average) for ten U.S. urban sites. Stevens et al.[16] accounted for more than 80 percent of fine particle mass in their analysis; other components were ammonium sulfates, nitrate, organic carbon, and a very small amount of lead. Since the other components of fine particle mass are essentially colorless, elemental carbon accounts for all of its color. Wolff et al.[19] found elemental carbon concentration accounts for essentially all the color in filtered particles.

There are also very few constituents of coarse particles. Since coarse particles are composed mostly of dust, the color of the coarse particle collection surfaces usually reflects nearby soil color. Chemical analysis of coarse samples conventionally reveals substantial levels of silicon and aluminum, elements which are unlikely to impart color, especially since they are present primarily as oxides or silicates. In some samples, the only transition metal present is iron, which usually accounts for 3 to 8 percent of coarse particle mass.[9] It is suggested that iron is the only component of the clay minerals present in coarse particle samples which can account for the red color frequently seen in dichotomous sampler coarse collections.

Microscopical examination of filter samples has suggested the possibility of two other colored particle components. Draftz and Severin[20] and Draftz[21] have reported the presence of small amounts of tire wear debris, estimated to account for about 1 percent of the coarse particle mass in most samples.[22] Since rubber tire tread contains about 40 percent, by mass, carbon black, this material is intensely colored. In addition to the rather lightly colored soil and calcite from asphalt roadways, there is sometimes present some larger oil soot material in urban samples.[21] Possibly this material comes from soot initially deposited on boiler tubes and displaced into the air in daily steam-cleaning.

Thus, the colored components of the coarse particulate material are not significant contributors to coarse particle or TSP mass. Further, the most

highly colored substance present in atmospheric particles is present almost exclusively in the fine particles (combustion-produced soot).

Measurement Scales

For the reasons discussed above, standard measures of soiling and of effects of soiling are not yet available. To provide such measures, two questions must be answered:

1. How are physical measures of soiling related to perceptual measures of soiling?

2. What are the economic consequences of soiling?

The following comments address the first question by considering how physical measures (materials deposited) and psychological measures (perceived dirtiness) of soiling may be related and how measures might be made. The second question, which involves possible efforts to change those levels, is not addressed.

Any model of soiling and its effects on behavior must relate physical measures (amount of particles deposited) to perceptual measures (what particle accumulation can be seen) and to cost measures (the value of removing soil). As with any model, it is necessary for each measure to be on a commmon scale; otherwise, one would be comparing apples and oranges. Since scales available to physics and perception or behavior are often different, it is useful to briefly discuss this issue.

Many measures in physics (distance, weight, time) provide ratio scales. Ratio scales have a true zero, and transformation between scales is achieved by multiplication by a constant. Length provides an example. Zero distance (no length) is meaningful, X centimeters can be converted to a comparable number of inches by multiplying by 2.54, and it is correct to say that twenty meters is twice ten meters.

Not all physical measures are on a ratio scale. When the air temperature changes from 32° to 64° Fahrenheit, the air becomes 32 units warmer on that interval scale. But the air does not become twice as warm. For interval scales, each step represents a constant amount of the domain measured, and zero is a convention rather than a description of nothing. Thus, while multiplication by a constant is sufficient to translate between ratio scales, translation between interval scales require the form

$$x' = ax + b$$

As examples, degrees $^{\circ}F = (9/5\ ^{\circ}C + 32)$; 32° Fahrenheit is equivalent to 0° Celsius; and neither $0^{\circ}F$ nor $0^{\circ}C$ means there is no temperature.

Ratio scales are difficult to achieve in perception and other branches of psychology. There, most scales available are interval or less (e.g., ordinal scales where the order among objects is known but the scale-steps between objects may not be equivalent in size; and nominal scales where objects can be named but the names are not related along any continuum.

These brief comments call attention to the fact that models to relate physical and perceptual measures will be limited by the available scales. If a model is constructed from data obtained on an interval scale of measurement, and if that model uses a linear equation to extrapolate predictions beyond the range of the data, then this procedure will often result in incorrect predictions. This fact cautions the importance of knowing the scale on which measurements are made. Additional cautions are discussed next.

Psychophysics

One task of the discipline known as psychophysics is to relate psychological and physical scales. Three factors beyond the issue of scale type are essential to consider: the absolute threshold, the differential threshold, and context.

1. The absolute threshold. Physical zero and psychological zero often do not match up. This is because there are absolute thresholds for perception. A finite amount of physical energy is needed for a stimulus to have a measurable perceptual effect. The magnitude of this threshold depends on several factors: the stimulus, where and how it is presented, and whether the person is prepared for it. For example, whether or not a weak light will be reported as present depends on the light (number of photons, areal size, wavelength composition, duration), whether it is presented to the center of the eye or to the periphery (or to the back of the head which assures a high absolute threshold), temporal characteristics, whether the observer is dark adapted, and whether a light is expected. Simply, psychological zero is different from physical zero.

2. The differential threshold. If a set of lights appears to differ in equal brightness steps, then the physical intensity steps between the lights must differ exponentially. This reflects Weber's law:

$$\text{delta } I/I = k$$

where I is the intensity of a light, and delta I is the amount by which the light must be changed from I in order to be perceived as different from it. The proportionality constant, k, means the ability to discriminate between lights is relative to I. Weber's law holds over most of the operating range of all senses and the value of k depends on the sense. Perceptual systems operate on relations. This means that any ruler or other scale to demark equal brightness steps (or darkness, dirtiness, etc.) maps logarithmically onto a scale of physical intensity. Simply put, most physical and psychological scales are not linearly related.

3. Context. The absolute and differential thresholds are measures of the amount of some energy in terms of some criterion when the energy is presented out of nothingness, as when a light is turned on in the dark. If, however, measures are taken when energy is presented in some intensive environment, then the importance of the surround becomes apparent and a relative threshold must be measured. This provides a measure of context effects.

Consider a disc surrounded by an annulus as depicted by the upper portion of Figure 2.[23] The observer's task is to report the brightness of the disc or the brightness of the annulus. For brevity, only disc brightness is considered here. An observer adjusts the intensity of the spot of light beside the disc-annulus until that spot and the disc appear equal. This is when the disc and the spot have the same brightness.

For a disc of some intensity (the parameter in Figure 2b), the intensity of the matching spot (the ordinate of Figure 2b) depends on the intensity of the annulus (the abscissa of Figure 2b). Consider the upper-right curve as an example. For a disc luminance of 1.55 Log milliLamberts, the spot luminance needed to match the disc varies by 3½ log units (the brightness measure ranges from 1.5 to -2 Log mL) as the intensity of the annulus varies by 1½ log units). That is, the physically unchanged disc changes in appearance from nearly white to nearly black as the intensity of the annulus changes from grey to nearly white.

There are everyday examples of this class of effect on appearances. One is seen by cutting in half a piece of grey paper or uniformly dirty paper. If one half of this paper is placed on a black surface and the other half is placed on a white surface, then the two physically identical halves will appear different. The paper appears lighter on the black surface.

This experiment and example mean that physical measures to predict the appearance of a region require, as well as a measure of the luminance of the region, measures of the luminances of other regions in the field. Figure and ground, or the contrast between figure and ground, must be measured in any evaluation of brightness or darkness or dinginess.

Any model to relate physical soiling to perceived soiling and to some costs of soiling must use the appropriate measurement scales. For example, if measures are extrapolated to the 0-0 origin to construct some linear model relating physical dirt to dollar cost, costs would be underestimated. This is because the perceived dirt threshold begins at a value greater than zero physical dirt; thus such a scaling procedure would produce an overly shallow slope for the prediction equation. A similar difficulty occurs if perceived dirt and physical amounts of dirt are assumed to be linearly correlated. These are almost surely related by a power function having an exponent less than one, in which case extrapolation by a model beyond data would produce prediction errors in the other direction.

Surface Properties

For something to appear dirty there must be a perceived surface change from the clean state. This requires that a deposit alter the reflectance of the surface. If the deposit is superimposed on a surface having the same reflectance values, then there is no visible soiling (felt grit or dirtiness are not considered here). Too, if white particles are deposited on a slate shelf, then the shelf is dirty -- even though no "dirty" particles have landed on it. When surface materials are the color of the soil particles, then soiling is less a nuisance. It is contrast between particles and surface that leads to perceived soiling. It was not only availability of the material that led architects in the Southwestern U.S. to build with adobe. Soiling due to sand storms is more difficult to notice than if the buildings were of white clapboard. Those are used in New England where the salt air covers things

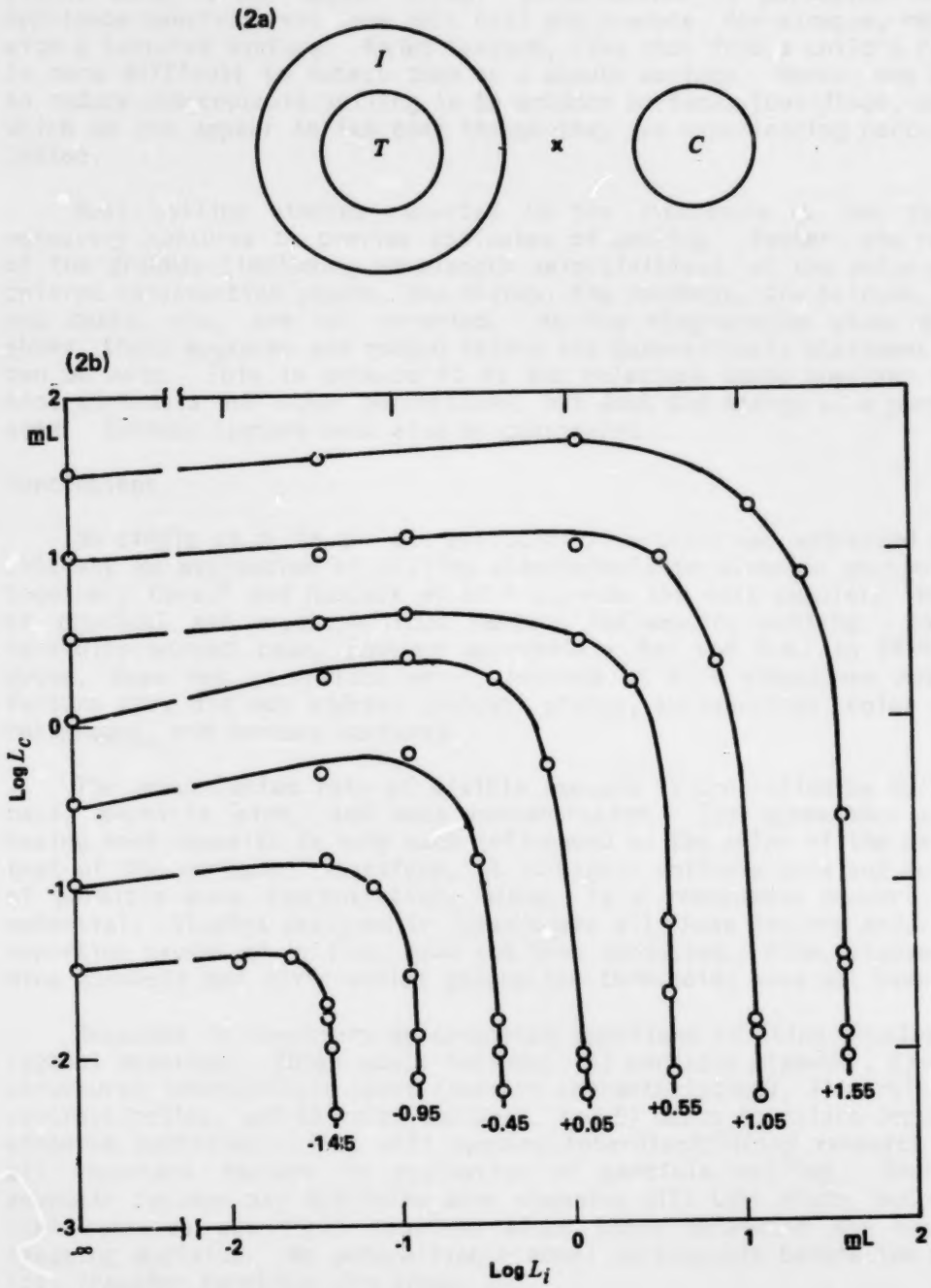

Figure 2. (a). Stimulus patterns used to measure brightness. A test field (T) is surrounded by an inducing field (I). The appearance of T is matched by the observer adjusting the intensity of C. (b). The intensity of C (ordinate) needed to match T for values noted on the abcissa and for values of I noted as a parameter.[23]

white. Thus, color of the soil and the soiled background material should routinely be reported in soiling studies along with reflectances.

Another of the many factors that contribute to contrast is texture. An area which is uniformly soiled may appear clean. If that same amount of soil is structured, as when washed a bit by the rain or partially wiped with a cloth, then it may appear dirty. Distribution of particles is an issue. Appliance manufacturers know this well and produce, for example, refrigerators with a textured surface. Added texture, like that from a child's fingerprints, is more difficult to detect than on a smooth surface. Hence, one possibility to reduce unacceptable soiling is to produce surfaces (buildings, desks, etc.) which do not appear soiled even though they are experiencing particle accumulation.

Most soiling studies reported in the literature do not report these necessary measures to provide estimates of soiling. Rather, the reflectances of the grounds (including wavelength selectivities), of the white papers, the colored construction papers, the dishes, the roadways, the bridges, the tables and desks, etc. are not reported. As the ring-annulus study of Figure 2 shows, those measures are needed before any generalizable statement of soiling can be made. This is because it is the relations among energies that determine dirtiness and other perceptions, not just the energy of a portion of the area. Surface texture must also be considered.

Conclusions

No single study in the air pollution literature has addressed all factors relevant to evaluation of soiling attributable to airborne particles. Taken together, Carey[8] and Hancock et al.[1] provide the most complete investigation of physical and psychophysical factors influencing soiling. Carey's very carefully worked case, however appropriate for the U.K. in 1959, as noted above, does not generalize well. Hancock et al.[1] themselves noted several factors they did not address (subject status, surroundings, color of dust and background, and surface texture).

The accumulation rate of visible deposit is controlled by surface roughness, particle size, and mass concentration. The appearance of surfaces having such deposits is very much influenced by the color of the particles and that of the surface. Therefore, it is highly unlikely that any current index of particle mass concentration, alone, is a reasonable measure of soiling potential. Studies designed to interrelate all those factors and, in fact, to apportion causes of soiling, have not been conducted. Also, studies to determine absolute and differential perception thresholds have not been conducted.

Research is necessary to construct equations relating physical and perceptual measures. These would include: 1) particle diameter, 2) uniform and structured interparticle space (surface characteristics), 3) particle/surround contrast ratios, and 4) color contrast, and 5) means to relate deposit back to airborne particles. This will require interdisciplinary research to include all important factors in evaluation of particle soiling. Sociometric or economic factors may determine when cleaning will take place, but psychophysical measures are first required since those determine the basis for the cleaning decision. No generalizable model is possible before the psychophysical transfer functions are known.

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Though this information was prepared in part by employees of the U.S. Environmental Protection Agency, it has not been subjected to Agency peer and administrative review. Therefore, the conclusions and opinions drawn are solely those of the authors and should not be construed as those of the Agency.